EXPERIMENTS WITH "THIN" ELECTRON BEAM AT GOL-3

V.V. Postupaev[1,2], A.V. Arzhannikov[1,2], V.T. Astrelin[1,2], V.I. Batkin[1], A.V. Burdakov[1,3], V.S. Burmasov[1], I.A. Ivanov[1,2], M.V. Ivantsivsky[1], K.N. Kuklin[1], S.A. Kuznetsov[2], M.A. Makarov[1], K.I. Mekler[1], S.V. Polosatkin[1,2], S.S. Popov[1], A.F. Rovenskikh[1], A.A. Shoshin[1], S.L. Sinitsky[1,2], V.F.Sklyarov[3], N.V. Sorokina[3], A.V. Sudnikov[2], Yu.S. Sulyaev[1], L.N. Vyacheslavov[1]

[1] Budker Institute of Nuclear Physics, 11 Lavrentjev Avenue, Novosibirsk 630090, Russia
[2] Novosibirsk State University, 2 Pirogova Street, Novosibirsk 630090, Russia
[3] Novosibirsk State Technical University, 20 Karl Marx Avenue, Novosibirsk 630092, Russia
e-mail: V.V.Postupaev@inp.nsk.su

The latest experimental campaign at the GOL-3 multiple-mirror trap was mainly aimed at features of heating and stability of the electron-beam-heated turbulent plasma. The discussed experiments feature a reduced-cross-section electron beam with the current decreased down to 1÷1.5 kA at the current density of ~1 kA/cm^2 (the same as in the "full-scale" experiments). The hot plasma cross-section decreased correspondingly.

Lowered current of the electron beam became less than the critical vacuum current. This gives the possibility to make a direct comparison of regimes with the beam injection into a neutral or a preliminary ionized deuterium. New experimental results will be presented on the beam relaxation in the plasma and on heating and stability of the reduced-cross-section plasma with low central safety factor q(0)~0.3. Stabilization of some MHD modes by a controlled coupling of the plasma with an exit receiver plate was demonstrated.

I. INTRODUCTION

Main physical task for GOL-3 is the development of physics of a multiple-mirror plasma confinement for fusion.[1] Relatively high density and short plasma lifetime in the trap require a high-power heating system. Relativistic electron beam is used for this purpose. The plasma heating and confinement in the trap are of essentially turbulent nature. A keV-range electron temperature was obtained (see, e. g., Ref. 2) due to 1000-fold turbulent suppression of axial heat losses during the beam pulse[3] that is provided by a high-level Langmuir microturbulence, excited in the process of the beam relaxation in the plasma. The turbulence also facilitates plasma currents to create a sheared magnetic field which provides MHD stability.[4] In general, achieved plasma parameters support our vision of a multiple mirror trap as the alternative path to a fusion reactor with β~1 and 10^{21}÷10^{22} m^{-3} plasma density. Practical feasibility of the reactor will heavily depend on a level of required beam power.

The latest experimental campaign at the GOL-3 multiple-mirror trap was mainly aimed at features of heating and stability of the electron-beam-heated turbulent plasma. The feature of the operation regime is a significant reduction of full current and full cross-section of the electron beam. Cross-section of the beam-heated plasma becomes therefore small comparing with the full plasma size. Significance of the transverse transport from the turbulent plasma core increases. On the other hand, the current density in the electron beam stays the same as in full configuration. This means that, as before, the safety factor *q* can be less than unity within the beam cross-section. Such situation should be unstable, so specific measures were undertaken to provide good beam transport through the plasma column.

This paper presents new data from this experimental regime, especially concerning beam transport, heating of the plasma and stability of the beam-plasma system and features of operation with non-ionized gas at the beam start.

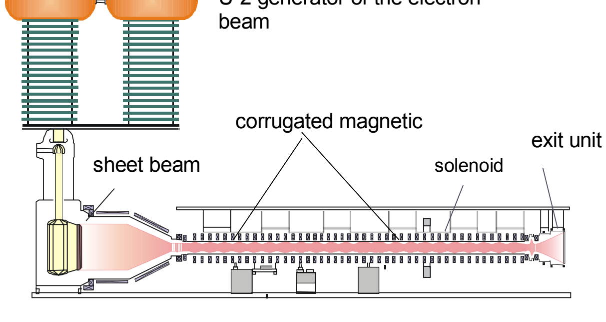

Fig. 1. Layout of GOL-3.

II. OPERATION REGIME AND DIAGNOSTICS

Deuterium plasma of $(2\div8)\cdot10^{20}$ m^{-3} density is confined in a 12-meter-long solenoid, which produces axially periodical (corrugated) magnetic field (Fig. 1). In the basic operation regime the solenoid consists of 52 magnetic corrugation periods (cells of multimirror system) with 22 cm length each and B_{max}/B_{min}=4.8/3.2 T (mirror ratio R=1.5). The solenoid terminates in single magnetic mirrors with a field of 8÷9 T. Initial density distribution along the axis is a bell-shaped profile (due to used gas-puffing technology), some dense gas is also puffed into the beam compression area – see Fig. 2. This profile slightly differs from the profile in standard configuration due to different gas flow in the vicinity of the input limiter, which restricts the beam diameter.

The plasma is heated up to ~2 keV (at ~10^{21} m^{-3} density and τ_E~1 ms) by a high-power relativistic electron beam (~0.8 MeV, ~20 kA, ~12 μs, ~120 kJ). A feature of new experiments is reduction of diameters of the beam and of the heated plasma to 13 mm (see Fig. 3). A small central part was cut from the standard beam by means of a graphite limiter placed in the area of a final beam compression before the solenoid. Further in the text such beam will be referred as the thin beam. The current density of the thin beam in the plasma remained at the same level of ~1 kA/cm^2 as for the full-sized one and quality of the thin beam is slightly better because of smaller average pitch angle due to smaller own magnetic field at the beam edge.

Typical parameters of the thin electron beam are shown in Fig. 4. Here we should note that, as it was stated earlier, the thin beam was created from the full-scale one by dumping of the main fraction of primary electron beam to a graphite limiter. Reliable measurements of the beam current can be done in clean vacuum conditions only. Breakdown of a gas or a plasma appearance mimic the beam current with plasma currents, so adequate waveforms of the beam current were obtained in a special shots with low beam current. One of such shots is shown in Fig.4, the beam current in a standard shots is higher and its amplitude can be estimated as ~1.5 kA from the initial parts of the waveforms.

In shots into the preliminary plasma compensation of the beam plasma by the return plasma current is almost perfect in regimes with good confinement. The net current waveform follows the waveform of the discharge current – see Fig. 5. This Figure displays waveforms of 8 Rogowski coils at different coordinates which coincide within the calibration accuracy (raw signals of Rogowski coils without correction for slightly different self-integration time are shown).

Standard set of GOL-3 diagnostics was used. Some of the systems and new physical results are reported in separate papers in more details (proper references are given in the text).

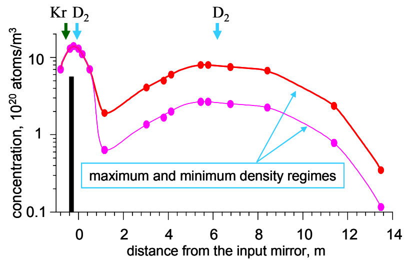

Fig. 2. Initial gas density distribution along the axis in the discussed experiments. Three vacuum valves fire with a preset sequence. Bold black line corresponds to location of input limiter which absorbs the rest of the beam.

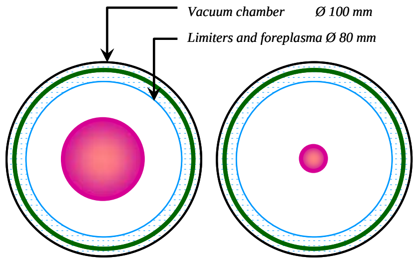

Fig. 3. Comparison of the beam-heated cross-section of the plasma (inner circles) with cross-sections of the vacuum chamber and limiters. Left part of the Figure corresponds to normal operation regime, right part corresponds to experiments with the thin beam.

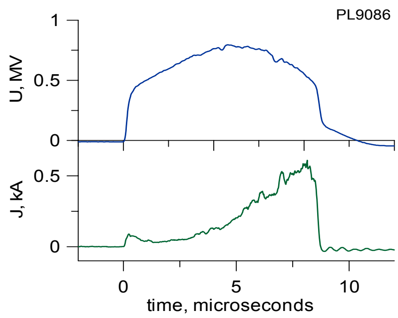

Fig. 4. Waveforms of the diode voltage and of the beam current (vacuum shot shown, in plasma shots the beam current reaches ~~1.5 kA).

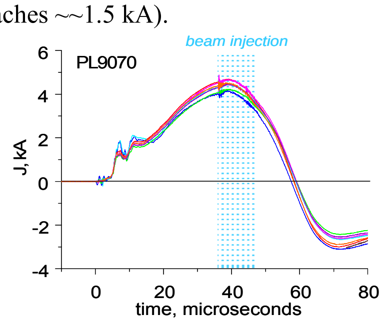

Fig. 5. Net plasma current. Preliminary plasma starts at t=0, the beam duration is shaded. Waveforms of 8 Rogowski coils placed at different coordinates are shown.

III. BEAM RELAXATION IN THE PLASMA

Energy spectrum of electrons at the output of the beam from the plasma determines the degree of the beam relaxation in energy and its average energy losses. It also allows estimating the energy density of resonant with the beam Langmuir fluctuations. The energy spectrum was measured with simple and reliable diagnostics,[5] based on an energy dependence of range of electrons in an absorber. Electrons passed the trap were dumped in a stack of metal foils. Having measured the currents from the foils one can reconstruct the energy spectrum of incident electrons.

Two sets of waveforms are shown in Fig. 6. The upper part corresponds to a calibration shot into vacuum with the beam of decreased energy. Signals from the analyzer of the exit beam spectrum are continuous and last for expected duration despite being heavily spiked due to known microstructure of the beam. At the same time in a typical shot with the plasma the same signals undergo simultaneous breaks and recoveries. The quantity and duration of such breaks varies from shot to shot, while exit bremmstrahlung always remains continuous. The relaxation efficiency remains practically constant over those fragments of waveforms where such calculation is possible. Such situation can be explained by the beam footprint displacement with the amplitude which is comparable with its diameter.

Intense relaxation of the beam in the plasma is accompanied by essential broadening of the energy spectrum and its shift to lower energies of electrons. A group of electrons with energies in the range 30÷100 keV is observed; this group consists of both strongly decelerated electrons of the beam and accelerated electrons of the plasma. The density of this group is comparable to the beam density. Average loss of the beam energy in the plasma estimated from the energy spectrum in the range 0.1÷0.8 MeV exceeds the level of 50% (see Fig. 7). At the beam injection into a neutral gas the plasma heating efficiency decreases, the average loss of the beam energy is somewhat lower and does not exceed 35÷40 %. Details can be found in Ref. 5.

Smaller than before diameter of the beam results in interesting change of nature of $2\omega_p$ emission from the plasma, which is a good indicator of existence of strong Langmuir turbulence in the plasma. Details of such measurements are described in Ref. 6. In contrast to a full-sized beam, in these experiments waveforms of $2\omega_p$ emission became highly irregular – see a fragment of full signal in Fig. 8. Each waveform can be considered as combination of a short spikes of different intensities and 5-10 ns duration. The most probable explanation of such behavior is that microwave emission at double plasma frequency origins from a compact plasma regions with a high level of turbulence. Thus such $2\omega_p$ spikes can be an indirect argument for density caverns predicted in Ref. 7.

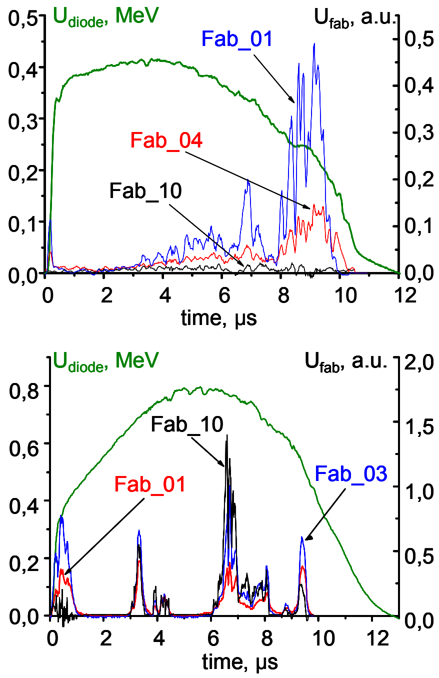

Fig. 6. Waveforms of the diode voltage (smooth curves) and of three channels of the multifoil analyzer of the beam spectrum. The upper part is for a shot into vacuum, the lower part is for a shot into the plasma.

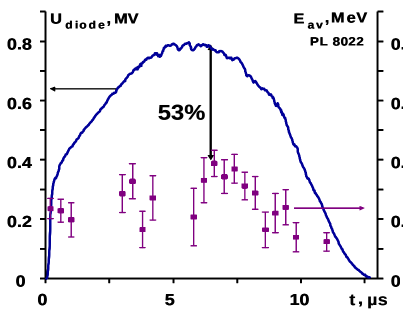

Fig. 7. Time dependencies of the initial beam energy (the diode voltage) and average energy of electrons in the range 0.1÷0.8 MeV at the plasma exit.

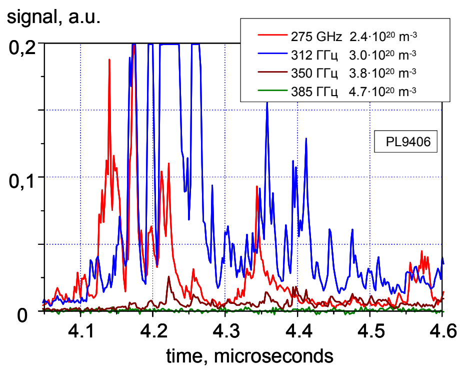

Fig. 8. Fine structure of $2\omega_p$ emission.

IV. FEATURES OF THE PLASMA HEATING

At the reduction of the beam diameter the ratio of the hot plasma cross-section to its perimeter worsened. Accordingly, the role of transverse energy and particle losses increases comparing with the standard operation mode with a good confinement where transverse losses do not exceed 10% in global energy balance. Spatial distribution of axial currents flowing along the plasma changes also, i.e. helical structure of the magnetic field in the confinement area (on which quality of the plasma confinement in GOL-3 depends[4]) changes too. Otherwise, local beam-plasma interaction expected to be the same.

Results of experiments with the thin beam appeared more interesting, than it was expected. The plasma heating within some interval at first two meters from the beam injection point appeared better, than it was expected at simple recalculation for the new diameter of the electron beam (see Fig. 9). There is a pressure maximum in axial distribution at this coordinate for the thin beam (Fig. 10) while for a full-sized beam this maximum is displaced closer to the input mirror and has smaller amplitude. At the rest of the plasma column the beam moves through the plasma already in partially relaxed condition so the plasma heating coincides with that was observed with the standard beam, as it was expected. Energy values were normalized for 4 T magnetic field corresponding to the mean field in the corrugation cell. Formally calculated plasma β value in the "hot spots" reaches 35% for the waveforms shown in Fig.11 with no specific signs of any fast instability. Some provisions should be made however that this figure implies that almost all the energy says within the calculated size of the hot zone that has to be confirmed by some other method.

Simultaneous measurements in two radial points by a Thomson scattering system were done[8]. At the stable beam transport the axis should always be hotter than the edge, such situation is presented in Fig. 12. Nevertheless the reverse and other cases were also observed. Such behavior also evidences for large shot-to-shot displacement of the beam position. The observed displacement at the Thomson scattering system location is still small enough and the beam remains within the preliminary plasma cross-section.

V. SHOTS INTO NEUTRAL GAS

The beam current becomes essentially less than a limiting vacuum current. Thus experiments became possible not only with injection of the beam in the low-temperature start plasma, but also with the beam injection into vacuum and into a non-ionized gas. Two latter cases are unavailable with the full-current electron beam, where fast development of the Kruskal-Shafranov instability occurs with the beam dump to the wall. Efficiency of the beam relaxation in the gas is about twofold worse than in

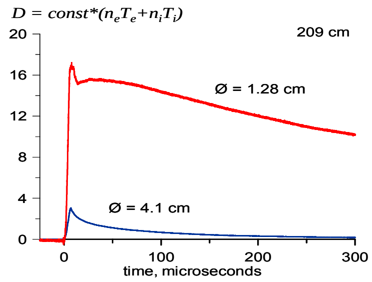

Fig. 9. Dynamics of plasma pressure from diamagnetic measurements for the cases of thin and standard electron beams at 209 cm distance from the input mirror. Waveforms are normalized for calculated vacuum cross-sections of the electron beam.

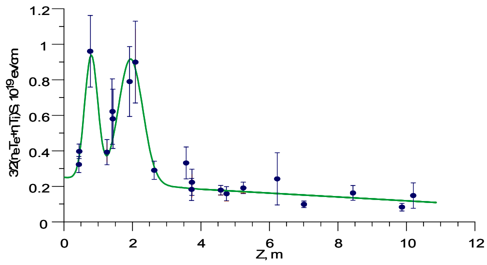

Fig. 10. Axial dependence of plasma energy content per unit length. Statistical spread for a series of 30 shots is shown. Central density is $n_0 = 3{\cdot}10^{20}$ m^{-3}.

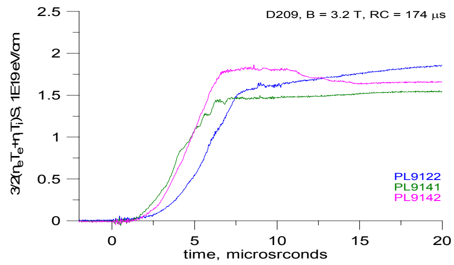

Fig. 11. Dynamics of diamagnetism in best shots in the "hot spot" at 2.09 m. Some growth after the beam end is due to isotropization of fast plasma electrons in the velocity space. Central density is $n_0 = 3{\cdot}10^{20}$ m^{-3}.

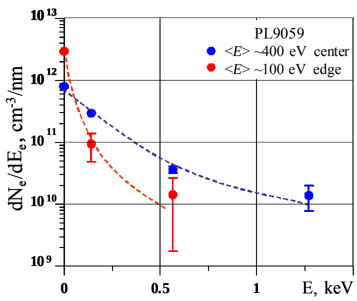

Fig. 12. Energy spectrum of plasma electrons measured by a Thomson scattering system simultaneously for the point at the axis (at the expected beam center) and 6 mm apart (at the expected edge of the beam-heated zone).

the plasma.[5] The same twofold difference was observed for the peak energy which the beam leaves in the plasma. Similar conclusion on significant role of preliminary ionization was earlier made in Ref. 9 with shorter plasma column in uniform magnetic field.

Experiments with the non-ionized gas enable studies of formation of the return current which in turn creates the edge plasma. At the beam current density of ≈1 kA/cm^2 the safety factor $q(0) \approx 0.3$ (see Ref. 4), so the beam-plasma system should be unstable. Displacement of the beam from its expected position was observed by spatial distribution of VUV emission of impurity ions and by radial profiles of NBI attenuation. Observed time-integrated VUV profile is broader than the expected one (see, e.g., Fig. 13). The electron beam appeared displaced to different points of plasma section from shot to shot.[10] Thus the beam transportation through the plasma was steady as a whole, i.e. the beam dump to the chamber wall with fast plasma decay was not observed. Energy confinement was good in general. The observable phenomena can testify that the instability really develops, but displacement of the beam saturates possibly because of self-organization of the plasma and formation of specific stable structure of return plasma currents in it.

Interesting that ionization of the gas and formation of the edge plasma occur not only within the expected beam cross-section but in the whole cross-section of the vacuum chamber. Therefore evolution of the beam-plasma system at later stages of the experiment is similar to that observed in the experiments with the preliminary plasma.

VI. STABILIZATION OF THE BEAM TRANSPORT

As was already mentioned, displacement of the beam from the axis was observed. This displacement does not dump the beam to the wall; this means that amplitude of the displacement was limited. This differs the case from the Kruskal-Shafranov instability which was observed earlier in unstable GOL-3 operation regimes.

Several causes of the observed instability are possible. One of them is an asymmetry of return plasma current. In the discussed experiments the exit beam receiver was placed in the low-field part of the exit expander in order to decrease the specific energy load to its surface down to allowable level. Such placement of the receiver complicates formation of the return current through the plasma column; therefore the return current can became non-axisymmetrical. This in turn can provide displacement of the beam as a whole and loss of its shape.

A special experimental series with varied conditions of formation of the return current was completed to check this assumption.[11] For this purpose a heavy gas (krypton) was puffed in the vicinity of the beam receiver. Net puffed mass and gas distribution along the axis were varied in the experiments.

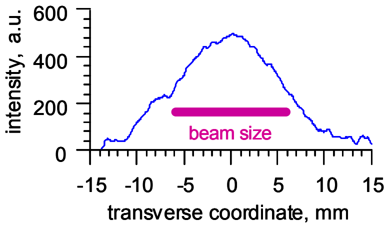

Fig. 13. Radial profile of OV 76.0 nm emission (beam shot into the gas).

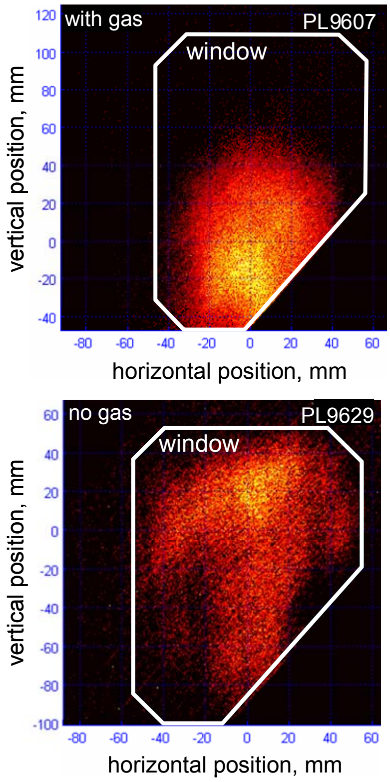

Fig. 14. Hard X-ray images of the exit beam footprint. Exposure is 1 μs. Top: with krypton puffing, bottom: no puffing. White contour shows the field-of-view of the X-ray imager. Camera position is slightly diggerent.

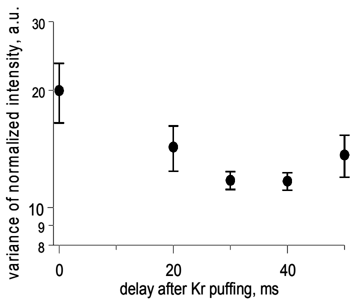

Fig. 15. Dependence of asymmetry of the X-ray image of the beam footprint on the delay of the plasma start after the krypton puffing. Optimum at ~35 ms corresponds to krypton density $n_{Kr} = 1.5 \cdot 10^{21}$ m^{-3}.

Displacement of the footprint from the expected position and change of its shape were detected with an X-ray imaging system in own bremsstrahlung of the beam. Right part of Fig. 14 shows a typical image of the footprint which is distorted and non-symmetric. Krypton puffing near the beam receiver improves the footprint shape and position. The gas-puffing technology results not in absolute but in statistical improvement of the beam transport. Averaged over large series of shots improvement occurs with the reduced deviations of the beam shape and position in optimal gas-puffed regimes (see Fig.15). Similar statistical improvement is also visible from several other diagnostics, including magnetics and wall bolometers (Fig.16).[11] Bolometry shows that good shots can appear with and without the puffing, but the gas puffing eliminates events with extremely high transverse losses.

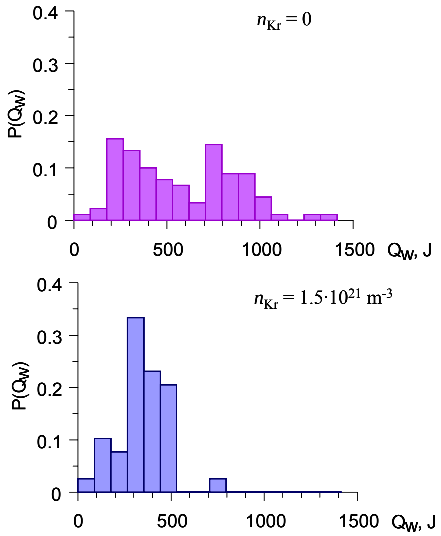

Fig. 16. Full energy lost to the wall without and with gas-puffing. Probabilities of getting a specific wall losses are shown.

IV. SUMMARY AND DISCUSSION

The beam-plasma interaction within the parameter space typical for GOL-3 experiments features several important nonlinear and collective processes. The goal of the discussed experiments was to check a possibility of significantly reducing the beam power while keeping the plasma parameters at a high level. Such data is important for considering fusion prospects of a multiple-mirror reactor with an electron beam.[1]

Experiments confirmed in general understanding of underlying physics at tenfold-decreased beam power and plasma cross-section. Initial preionization is important for effective beam-plasma interaction. The beam with $q < 1$ partially loses stability but stays within the plasma. Conditions for generation of the return current are important for stable beam transport through the plasma column. Improvement of the stability was demonstrated.

The experiments partially verified feasibility of plasma heating at lowered beam parameters. This is important for the next planned step in GOL-3 program.

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